Renewable and Sustainable Energy Reviews 98 (2018) 255–267

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A review of the potential impacts of climate change on bulk power system planning and operations in the United States

Michael T. Craig[a], Stuart Cohen[a], Jordan Macknick[a], Caroline Draxl[a], Omar J. Guerra[a], Manajit Sengupta[a], Sue Ellen Haupt[b], Bri-Mathias Hodge[a], Carlo Brancucci[a,*]

[a] National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, CO 80401, United States
[b] National Center for Atmospheric Research, 1850 Table Mesa Drive, Boulder, CO 80305, United States

ARTICLE INFO

Keywords:
Climate change
Power system
Climate change impacts
Power system planning
Power system operations

ABSTRACT

Climate change might impact various components of the bulk electric power system, including electricity demand; transmission; and thermal, hydropower, wind, and solar generators. Most research in this area quantifies impacts on one or a few components and does not link these impacts to effects on power system planning and operations. Here, we advance the understanding of how climate change might impact the bulk U.S. power system in three ways. First, we synthesize recent research to capture likely component-level impacts of climate change in the United States. Second, given the interconnected nature of the electric power system, we assess how aggregated component-level impacts might affect power system planning and operations. Third, we outline an agenda for future research on climate change impacts on power system planning and operations. Although component-level impacts vary in their magnitude, collectively they might significantly affect planning and operations. Most notably, increased demand plus reduced firm capacity across generation types might require systems to procure significant additional capacity to maintain planning reserve margins, and regional declines in renewable resources might need to be offset by increasing zero-carbon investment to meet decarbonization targets. Aggregated impacts might also affect operations, e.g., through shifts in dispatching and increased operational reserve requirements. Future research should aggregate component-level impacts at operational timescales, quantify impacts on wind and solar variability, and contextualize climate change impacts within ongoing shifts in the electric power system.

1. Introduction

While weather and climate have impacted power systems since their inception, two ongoing trends could fundamentally reshape this relationship. First, climate change will alter climate and weather during the next decades, inducing nonstationary trends in air temperature and precipitation [1] that might present power systems with new conditions and challenges [2]. In fact, utilities in Europe [3], Canada [4], the United States [5], and elsewhere have already started formulating plans to address these impacts. Second, because of declining costs [6] and decarbonization efforts [7], power systems are increasingly shifting toward variable wind and solar technologies (among other zero-carbon technologies).

Given these forces, a growing body of literature estimates how climate change might affect electric power systems. Most literature focuses on impacts to one or more components of the power system, including electricity demand [8]; transmission infrastructure [9]; and hydroelectric [10], thermal [11], wind [12], and solar [13] generation. Others during the last decade review aspects of climate change impacts on power system components. Stanton and Dessai [14] summarize supply-side impacts of climate change for each European country, Chandramowli and Felder [15] detail the models and methods used to assess climate impacts, Schaeffer et al. [16] describe the mechanisms by which climate change might affect each component of the electric power system, and Mideksa and Kallbekken [17] qualitatively summarize supply- and demand-side impacts globally. None of these prior reviews link component-level or aggregated component-level impacts to power system planning and operation impacts. Additionally, prior reviews do not quantitatively assess component-level impacts in the United States or other regions. Quantitative assessments indicate likely absolute and relative magnitudes of component-level impacts, which are crucial for prioritizing research and adaptation efforts. Despite increasing publications on individual power system components, a dearth of research exists translating climate change impacts on these

* Corresponding author.
E-mail address: Carlo.Brancucci@nrel.gov (C. Brancucci).

https://doi.org/10.1016/j.rser.2018.09.022
Received 19 July 2018; Received in revised form 24 August 2018; Accepted 18 September 2018
Available online 25 September 2018

components into impacts on power system planning and operations. Of most relevance, McFarland et al. [18] and Larsen et al. [19] assess how climate change impacts on electricity demand and thermal plant efficiency will drive increased investments and generation. Notably, both papers consider only a small subset of potential component-level impacts; however, because of the interconnected nature of the power system, concurrent impacts on multiple components might yield reinforcing effects on planning and operations. Thus, aggregating impacts and interactions of climate change across components of the power system and linking them to planning and operations is crucial to understand what actions, if any, need to be taken to maintain economic, resilient, and reliable electricity delivery in the future.

A challenge to this endeavor is the significant uncertainty in future climate change and its impacts on power systems. Uncertainty in future climate change arises primarily from a combination of model uncertainty (i.e., models imperfectly represent climate), future emissions pathway uncertainty (i.e., how quickly will economies decarbonize), and climate dynamics uncertainty (e.g., how do aerosols and clouds interact and what is the resulting radiative forcing) [20,21]. Even with perfect climate change foresight, the impacts of climate change on power systems would be uncertain because decarbonization and economic forces might reshape the composition and operation of the generator fleet in the coming decades. For one, retirements of fossil-fueled thermal units due to economic and environmental factors [22,23] will need to be compensated by other sources, particularly wind and solar [23,24]. Growth in wind and solar power might occur in resource-rich areas far from load, requiring significant transmission expansions [25,26]. Additionally, electrification of transportation and other services could significantly increase demand and alter temporal demand patterns [27].

Uncertainty in climate change and its power system impacts does not preclude its consideration in power system planning and operations, as planning and operations already account for large uncertainties. Planning accounts for uncertain load growth, retirements, investments, and emerging technologies, whereas operations account for uncertainty induced by short-term weather variability, e.g. in wind and solar generation [28] and forced thermal generator outages [29,30]. In this context, climate change impacts and associated uncertainty do not pose a fundamentally new problem to planning and operations, but rather add to the complexity and uncertainty they already account for.

In this article, we further the understanding of how climate change might affect bulk, i.e., transmission-scale, power systems by examining individual and aggregated component-level impacts on bulk power system planning and operations. Because studies on climate change impacts typically rely on data from Global Climate Models (GCMs), in Section 3 we briefly describe GCMs and discuss challenges with their use. In Section 4, we focus on climate change impacts on individual components of power systems. We review the results of recent research, then provide our assessments of research gaps and how component-level impacts may affect power system planning and operations. In Section 5, we focus on climate change impacts on power system planning and operations. We first provide our assessment of how aggregated component-level impacts of climate change might affect power system planning and operations, then outline our proposed future research agenda. Given recent publications in this area, we conduct our review for the United States. Additionally, we focus on the bulk power system, so we ignore distribution-level and upstream impacts (see [16] for the latter).

2. Methods

To conduct our literature review, we searched Scopus for peer-reviewed publications on climate change impacts on individual power system components and on power system planning and operations. Given the nascent stage of such research, we limited our search results to publications since 2010 that pertain to the United States. Table 1 provides our Scopus search terms and the number of publications

Table 1
For each component-level impact, our Scopus search terms, the number of publications returned by each search, and the number of publications returned by each search filtered for relevance.

Component-level impact	Scopus search terms	Number of returned publications	Number of filtered publications
Demand	Electricity AND climate change impacts	188	26
Thermal generators	Thermal plants AND power systems AND United States AND climate change impacts	11	19
	Fossil fuel* and power plant* AND United States AND climate change impacts	32	
	Power plant AND (coal OR gas OR oil OR fossil) AND United States AND climate change impacts	69	
Hydropower	(Hydropower OR hydrolog* OR hydro-climat*) AND United States AND climate change	1500	29
	Hydropower AND United States AND climate change impacts	45	
Wind	Wind generation AND United States AND climate change impacts	36	28
	Wind speed AND (wind power OR wind energy) AND climate model	562	
	Wind speed AND (wind power OR wind energy) AND United States AND climate model	252	
Solar	(Solar OR photovoltaic) AND power systems AND United States AND climate change impacts	21	22
	Solar generation AND power systems AND United States AND climate change impacts	13	
	Solar generation AND United States AND climate change impacts	27	
	Solar photovoltaic OR concentrating solar power) AND generation AND climate change impacts	120	
	(Solar power OR solar energy) AND United States AND climate model	130	
	Solar resource AND United States AND climate model	55	
Transmission	Transmission AND electric* AND climate change	485	19
	Transmission AND electric* AND United States AND climate change	37	
Planning and operations	Power systems AND United States AND climate change impacts	166	24

Table 2
Emissions pathway labels used in this review to facilitate comparison between RCPs and SRESs.

	RCP				SRES			
Emissions scenario	2.6	4.5	6.5	8.5	B1	B2	A1B	A2
Emissions pathway label	Low	Medium	Medium	High	Low	Medium	Medium	High

returned in each search. These searches mostly returned irrelevant publications, e.g. those related to climate change mitigation. As such, Table 1 also provides the number of publications from each search relevant to this review. To correct for potential issues associated with our Scopus searches, e.g. Scopus' exclusion of publications in the journal *Nature Energy* and potentially omitted search terms, we also reviewed cited and citing publications of select publications returned by each search.

Ideally, we would then combine the results of the resulting sets of publications through statistical analysis. However, the small number of published studies in each area and significantly diverging study scopes (e.g., from the city to national scale), methods, and types of reported results (e.g., plant- versus region-level results) preclude such an analysis. Instead, we further reduced the resulting sets of publications in each component-specific section (but not in the planning and operations sections) through our informed subjective judgment of paper quality. For these final publication sets, we report the results and caveats of each publication, then synthesize those results and caveats to estimate the likely range of and degree of agreement among studies on component-level climate change impacts. In so doing, we provide an initial estimate of the likely absolute and relative magnitudes of component-level climate change impacts, furthering our understanding of the relative importance of those impacts and the degree to which they might impact planning and operations.

3. Challenges with translating global climate model output to power system impacts

To forecast the impacts of climate change on power systems, most studies begin with trajectories of climate and weather variables output by GCMs. Given a future emissions scenario, GCMs use a system of equations to represent many aspects of the climate, including atmospheric circulation, land-surface interactions, atmospheric chemistry, cloud formation, and aerosols [1]. The modeled atmosphere is a chaotic, dynamic system that exhibits sensitivity to initial and boundary conditions. Therefore, even assuming the same future emissions scenario, GCMs produce different future climate trajectories because of differing model choices and assumptions [21]. Because of this uncertainty, many studies quantifying climate change impacts aggregate or compare output from multiple GCMs, such as those included in the Coupled Model Intercomparison Project (CMIP) [31]. Aggregating or averaging impacts among GCMs, however, can disguise natural variability and extremes—key considerations for power system planning and operations—and elide disagreement among models. Where possible in our review, we highlight GCM-derived uncertainty, such as by discussing agreement among GCMs. As GCMs continue to improve and more accurately replicate historic and predict future climate conditions, our understanding of climate impacts on all parts of the power system will also improve. As such, continued GCM research is a crosscutting research need.

One issue with GCMs is inadequate spatial and temporal resolutions. For instance, GCMs in CMIP5 have horizontal spatial resolutions of 50–350 km [1]. To obtain higher spatial resolution, GCM output is downscaled using dynamic or empirical statistical methods. In the former approach, GCM outputs set boundary conditions for regional climate models (RCMs), which then simulate physical processes at higher resolutions for a given region. RCMs typically use horizontal resolutions of 10–50 km [1]. Downscaling via RCMs, though, introduces additional uncertainties, such as parameterizing finely resolved processes. Empirical statistical downscaling, on the other hand, uses statistical analysis of historic data to map GCM output onto higher resolution scales [1]. The extent to which downscaling improves climate model performance—i.e., its accuracy in reproducing historic observations—varies with location, season, variable of interest (e.g., temperature versus precipitation), and other features [32].

Key inputs to GCMs are future emissions scenarios, which drive atmospheric concentrations of greenhouse gases and the severity of future climate change. Papers we review use two types of emissions scenarios: Special Report on Emission Scenarios (SRESs) [20] and more recent Representative Concentration Pathways (RCPs) [33]. Given differing assumptions underlying SRESs and RCPs [1], we do not map between the two. Instead, to facilitate comparison, we label each SRES and RCP scenario as a low-, medium-, or high-emissions pathway (Table 2) (see Supplementary information (SI) for additional details).

4. Climate change effects on individual components of the electric power system

In this section, we discuss the impacts of climate change on each component of the bulk U.S. electric power system. For each component, we synthesize recent literature to determine what, if any, agreement among studies exists regarding the direction and magnitude of climate change impacts. Based on this literature, we then provide our assessment of research gaps and link potential component-level impacts to impacts on power system planning and operations. Table 3 summarizes component-level impacts of climate change on which reviewed studies generally agree and consequent potential impacts on planning and operations.

Our discussion in this section has two notable limitations. First, reviewed studies largely ignore future potential changes in the power system, so climate change impacts we present largely pertain to the current system under future climate conditions. As such, we provide impacts in percentage terms to facilitate application to different future systems where possible. Second, climate change might increase the severity and frequency of extreme weather events, which in turn could affect all components of the bulk power system [1,2]. Given the dearth of studies on these effects, we do not discuss them here.

4.1. Electricity demand

Through shifts primarily in air temperature, relative humidity, and wind speed, climate change will affect building heating and cooling requirements, which in turn will affect the magnitude and timing of electricity demand. To quantify such impacts, researchers have used top-down and bottom-up approaches [15,34]. Top-down approaches regress historic load against variables such as temperature or degree days to estimate economy-wide demand [8,35,36], whereas bottom-up approaches input similar variables into building energy models to estimate demand for specific sectors or building classes [37–40].

Overall, reviewed top-down and bottom-up studies indicate that, holding other factors constant, rising air temperatures under climate change will likely increase average annual electricity demand in the United States by less than 5% through 2100 across emission scenarios [8,18,36,40,41] (Table 2). Changes in demand will likely vary significantly by region and season [8,18,36,41]. Reviewed top-down and bottom-up studies also broadly indicate that climate change will

Table 3
Impacts of climate change on each component of the U.S. bulk power system upon which reviewed studies generally agree and their power system planning and operations implications. For each impact, we provide our qualitative judgment of the degree of agreement among studies (low, medium, high), quality of available evidence (low, medium, robust), and our confidence in our evaluation of the impact (low, medium, high) [20].

Power System Component	Component-Level Impacts (Agreement among Studies, Quality of Evidence, and Confidence in our Evaluation)	Potential Power System Planning and Operations Implications
Electricity demand	Increased annual total and, to a greater extent, peak electricity demand (high, robust, high)	Increased total generation Increased investment requirement in generation or demand response and more peaked electricity prices
Thermal generators	Increased summertime curtailments largely contingent on enforcement of thermal discharge regulations (high, robust, high)	Reduced capacity value of thermal units, requiring additional capacity investments If curtailments correlated, increased operational reserve requirements
Hydropower	Reduced summertime hydropower resource in California and the Pacific Northwest (medium, medium, medium) Reduced annual hydropower resource across the South (medium, medium, medium)	Reduced capacity value, depending on release schedule and head height, requiring additional capacity investments Increased dispatching of other units
Wind	Decreased wind resources on average across the United States (low, medium, low) Large regional and temporal (seasonal and time of day) heterogeneity in wind resource changes (medium, medium, medium)	Increased wind investment or reliance on other zero-carbon technologies to meet decarbonization targets Regional changes in capacity values, requiring increased capacity investments
Solar	Decreased solar PV resource in California (medium, low, low) Increased solar PV and CSP resource in the Southeast (high, medium, medium) Greater average increases in CSP than solar PV resource across the United States (high, medium, high) Large regional and temporal (seasonal and time of day) heterogeneity in solar resource changes (medium, medium, medium)	Increased solar investment or reliance on other zero-carbon technologies to meet decarbonization targets Regional changes in capacity values, requiring increased capacity investments Increased investment in CSP relative to PV plants
Transmission	Reduced transmission capacity during peak demand periods (medium, low, medium)	Increased transmission investment Exacerbated congestion and contingencies

increase peak electricity demand more strongly than annual demand or by 10–20% more than current peak demand [8,36,40,42] (Table 4).

Despite general agreement among studies, opportunities for future research remain. First, many studies neglect shifts in population distributions and technology, although Allen et al. [35] incorporate population migration because of hurricanes, and Larsen et al. [19] incorporate technological and population change. Significant progress could be made by merging climate, population, and technology change, as in Kraucunas et al. [43], particularly because electrification of transportation and other services would increase demand [27]. Second, merging top-down and bottom-up approaches would supplement detailed thermodynamic building models with data frequently omitted in bottom-up approaches, e.g., industrial demand [40]. Examples of combined approaches include using complex multicomponent models [19] or embedding detailed building simulations in global integrated assessment models [44].

Growth in aggregate electricity demand and sharper growth in peak demand might have several effects on power system planning and operations. With respect to planning, growing peak demand will require increased capacity investments [8,18,40,45,46] in either additional generation or demand response programs that can reduce peak demand. New peaking units will likely have lower capacity factors than current peaking units because of increased growth in peak than total demand. Consequently, capacity payments might need to increase, and energy-only markets with price caps such as the Electric Reliability Council of Texas might struggle to maintain reserve margins. For system operations, increased total demand will require increased generation, potentially increasing costs and carbon dioxide (CO_2) emissions. Increased demand might also enable more demand response, enhancing grid flexibility while also permitting increased investment in inflexible generation, e.g., nuclear plants.

4.2. Thermal generation

Climate change might reduce the effective capacity and efficiency of thermal plants and increase the frequency of outages for thermal power plants through increased air and freshwater temperatures and reduced freshwater availability [10,47,48]. Thermal power plants include coal-, natural gas-, and oil-fired fossil-fueled facilities, which might be partly or fully phased out by 2050 for economic and environmental reasons [22,23], as well as biomass, geothermal, and nuclear facilities [49,50]. In 2015, more than 80% of electricity generation in the United States came from generators that rely on once-through, recirculating, or dry cooling [11]. For plants relying on freshwater resources for cooling, changes in annual and seasonal freshwater availability [51] and stream temperatures [10] under climate change might, depending on cooling water intake limits and environmental regulations, reduce their efficiency and capacity [10,48,52,53]. Notably, Ganguli et al. [54] find a correlation in historic and future GCM-derived data between low stream flows and high stream temperatures in the South, Southeast, and Great Plains and correlation between low stream flows and low stream temperatures in other regions. Because of increased required water withdrawals for cooling, plants with once-through cooling are particularly vulnerable to increasing freshwater scarcity and temperatures, whereas plants with recirculating and dry cooling are largely susceptible to air conditions, particularly temperature [50,55]. Increasing freshwater scarcity and temperatures also particularly threaten plants equipped with carbon capture and sequestration (CCS), which have larger cooling requirements than comparably sized plants without CCS [55,56]. Gas (or combustion) turbine capacities primarily vary with air conditions, particularly air temperature [50]. To estimate future thermal plant curtailments, studies typically use a sequence of GCMs, hydrology models, and thermodynamic power plant models [10,57], although Henry and Pratson [52] use plant-specific regressions linking historic air and water conditions to plant efficiencies and capacities.

Recent studies indicate that climate change will increase curtailments of thermal generators across the United States, particularly in the summer, but the degree to which they increase hinges on thermal discharge regulations. These regulations limit thermal effluent based on the resulting temperature and change in temperature of the body of

Table 4
Summary of recent studies on climate change impacts on electricity demand. For emission scenario details, see the SI.

Study	Modeling approach	Emission scenarios	Period of analysis	Region	Results
Fonseca et al. (2018) [42]	Top-down	RCP 8.5 (high)	End of century	Tennessee valley authority	Increase in average annual demand of 3% and 6% by midcentury and end of century, respectively Decrease in average winter demand of 4% and 6% and increase in average summer demand of 11% and 20% by midcentury and end of century, respectively Increase in 95th percentile of daily peak demand of 10% and 20% by midcentury and end of century, respectively
Auffhammer et al. (2017) [8]	Top-down	RCPs 4.5 (medium) and 8.5 (high)	End of century	Nationwide	Increase in average annual demand of 3% and 8% under RCP 4.5 and 8.5, respectively Increase in 95th percentile of daily peak demand of 7% and 18% under RCP 4.5 and 8.5, respectively Increase in frequency of days with peak demand more than 99th percentile of current demand of 4 and 15 times under RCP 4.5 and 8.5, respectively
Huang et al. (2016) [41]	Top-down	RCP 8.5 (high)	End of century	Nationwide	Increase in median residential and commercial building demand by 3% and 9% by midcentury and end of century, respectively Large variability in changes in median building demand by month, e.g. increase and decrease by 27% and 12% in September and January, respectively
Sullivan et al. (2015) [36]	Top-down	RCP 4.5 (medium)	Midcentury	Nationwide	Increase in average annual demand of 1% Increase in noncoincident peak demand of 5%
Dirks et al. (2015) [40]	Bottom-up	SRES A2 (high)	End of century	Eastern interconnection	Increase in average annual demand by residential and commercial buildings by 17% Increase in average peak demand by residential and commercial buildings by 42% High spatial variability in annual and peak demand increases; latter ranges from 6% (Virginia) to 136% (Minnesota)
McFarland et al. (2015) [18]	Bottom-up	Similar to RCP 8.5 (high)	Midcentury	Nationwide	Increase in average annual demand of 2–7% across two models

Table 5
Summary of recent studies on climate change impacts on thermal generators. Unless noted otherwise, results assume thermal discharge regulations are fully enforced. For emission scenario details, see the SI.

Study	Enforce discharge regulations?	Emission scenarios	Period of analysis	Region	Results
Miara et al. (2017) [11]	Yes	RCP 8.5 (high)	Midcentury	Nationwide	Average annual curtailments of up to 31% for plants with once-through, recirculating, and dry cooling Significant spatial variability in fleet-wide annual average curtailments, ranging from 2% (nationwide) to 17% (regional)
Liu et al. (2017) [53]	Yes and No	RCP 4.5 (medium)	Midcentury	Nationwide	With discharge regulations, average summertime capacity reductions of 8–14% and 8–10% for plants with once-through and recirculating cooling, respectively Without discharge regulations, average summertime capacity reductions of less than 3% for plants with once-through and recirculating cooling
Henry and Pratson (2016) [52]	No	NA	Historic	Central and East	Average summertime capacity reductions below 0.4% based on regression trained on historic data and applied to midcentury data from SRES A2 (high emissions) (per van Vliet et al. [10])
van Vliet et al. (2016b) [49]	Yes	RCPs 2.6 (low) and 8.5 (high)	Midcentury	Nationwide	Average annual curtailments of 5–15% across RCPs
Bartos and Chester (2015) [50]	Yes	SRES B1 (medium), A1B (medium), and A2 (high)	Midcentury	Western Electricity Coordinating Council	Average summertime capacity reductions of 7–10% for steam turbines and 1–4% for combustion turbines across emission scenarios
van Vliet et al. (2012) [10]	Yes	SRES B1 (medium) and A2 (high)	Midcentury	Central and East	Average summertime capacity reductions of 4–16% across power plants with once-through and recirculating cooling

water receiving the discharges [53]. If thermal regulations are fully enforced, reviewed studies indicate that summertime capacity curtailments could range from 5% to 30% across plant types by midcentury [10,11,49,50,53] (Table 5). In the absence of thermal discharge regulations, such as if generators obtain temporary waivers, reviewed studies find significantly lower capacity curtailments of 3% or less [52,53] (Table 5).

Several limitations exist in the current research that future work should address. First, future studies should explore trade-offs between curtailments and regulatory limits, which can significantly affect curtailments [53]. Second, future research should reconcile whether to enforce thermal regulations on plant effluent or mixed stream temperatures [53]. Third, to approximate future generator fleets, studies typically begin with the current generating fleet, then retire units based on plant lifetimes. Instead, studies should forecast generator additions and retirements more rigorously. Fourth, although Miara et al. [11] aggregate capacity curtailments by region, Macknick et al. [58] explore how demand response can offset thermal curtailments and Macknick et al. [59] embed cooling water availability in a capacity expansion model, studies otherwise do not contextualize curtailments in power systems. Future research should, for example, quantify capacity curtailments during peak demand periods, which Miara et al. [11] indicate differ from average capacity reductions.

Increased thermal curtailments under climate change might strongly affect power system planning and operations, although such effects would be moderated by an accelerated phaseout of fossil-fueled plants. With respect to planning, curtailments might reduce the ability of thermal units to contribute to meeting peak demand, i.e., their capacity value, particularly during droughts. Reduced capacity values might require additional capacity investments. Siting new power plants will also need to account for future water conditions. If power plants are consequently sited far from loads, interregional and intra-regional power flows and transmission investment requirements would likely increase. On operational timescales, capacity curtailments would require demand reductions or increased output by other generators, likely increasing costs. Correlated capacity reductions over large areas could threaten reserve requirements.

4.3. Hydropower generation potential

Climate change might affect hydropower generation potential primarily through shifts in precipitation volume and timing, snowpack amounts and melt timing, and evapotranspiration rates [1,57,60]. The extent to which each of these shifts will impact generation potential are likely to vary significantly between facilities with and without reservoirs and, among those with reservoirs, among facilities based on their storage volume and dependence on snowmelt [57,60]. Consequently, climate change impacts on hydropower generation potential will differ among and within regions and basins. To forecast hydropower generation under climate change conditions, studies typically input GCM or downscaled GCM output into one or more hydrological models, which account for water fluxes (e.g., evapotranspiration and soil infiltration) and routing given the local topology and stream network [57]. Water flows from hydrological models are then translated into generation via water management models that account for hydropower facility characteristics, such as storage volume, and reservoir operations, such as through rule curves. Rule curves guide hydropower operations by balancing competing demands for stored water across the year [57,61].

Reviewed studies generally forecast that climate change will reduce annual hydropower generation potential across the South (including the Southeast, South-central, and Southwest) and will reduce summertime generation potential in California. For both regions, Schewe et al. [62] find high (> 60%) agreement among GCMs and hydrology models of reduced annual river discharges under a 2 °C temperature increase (medium emissions). In California, many hydroelectric facilities rely on snowmelt and are therefore susceptible to changes in snowpack magnitude and melt timing [60,61,63]. Specifically, Tarroja et al. [61] find that less snow and earlier snowmelt might decrease annual hydropower generation potential in California by < 3% under RCP 4.5 and 8.5 (medium and high emissions) by midcentury. Larger reductions in annual hydropower generation potential will likely occur under climate change across the South [49,62,64,65]. Specifically, Schewe et al. [62] forecast that annual river discharges will decrease by more than 10% at a 2 °C temperature increase (medium emissions), whereas van Vliet et al. [66] forecast annual hydropower generation potential will decrease by 5–15% by midcentury under RCP 8.5 (high emissions) (or a roughly 3 °C temperature increase). Boehlert et al. [67] also forecast hydropower generation averaged over 17 GCMs will decrease by up to 13% annually across Southern regions by midcentury under a scenario similar to RCP 8.5 (high emissions). Conversely, Naz et al. [68] forecast annual flows into hydropower reservoirs in the Southeast averaged across 10 GCMs will increase up to 5% by midcentury.

For the Pacific Northwest, reviewed studies generally predict reduced summertime generation potential, but they disagree as to whether annual generation potential will increase or decrease partly because of disagreement among GCMs and hydrology models [62]. Hamlet et al. [69] forecast increased generation potential in the Pacific Northwest of 3–10% from October through March, decreased generation potential by 8–20% through the remainder of the year, and decreased annual generation potential of 3% under RCP 4.5 and 6.0 (medium emissions) by 2100. Kao et al. [70] also find decreased summer and increased winter generation potential by midcentury under RCP 6.0 (medium emissions). Similarly, across 17 GCMs, Boehlert et al. [67] forecast increased and decreased winter and summer average generation of 23% and 14%, respectively, under a scenario similar to RCP 8.5 (high emissions) and lesser changes under lower emission scenarios. On net, these seasonal changes yield increased annual average generation in the Pacific Northwest, which drives increased annual average generation nationwide. Other studies have reached conflicting results regarding annual generation potential, though, with some estimating annual generation increases [64] and others decreases [66,68,69]. In the rest of the United States, little agreement exists regarding trends in annual discharges among global climate and hydrology models [62].

Beyond continued improvements to climate and hydrology models, many research needs exist. First, little information exists on generation potential during extremely wet or dry periods or peak demand periods, which future research should explore. Additionally, future research should embed hydropower generation potential under climate change within power system models, which would indicate how generation potential changes might affect power system planning and operations. Two initial efforts in this area are Tarroja et al. [61] and Parkinson and Djilali [71], who input future hydropower generation into a dispatch model for California and a planning model for British Columbia, respectively.

Reduced annual and summertime hydropower generation potential in some regions might affect system planning and operations. Depending on head height and generation schedule changes, reduced summertime generation potential might reduce hydropower's capacity value, requiring replacement capacity investments or rule curve modifications. Rule curves could be modified to retain more water for peaking operations, e.g., by limiting early summer releases; however, changing rule curves would also affect competing water demands and restrictions, such as for flooding and irrigation. Reduced summertime generation must also be compensated with alternate generation or reduced demand, which might increase costs and/or emissions.

4.4. Wind generation potential

Changing weather under climate change might affect wind speeds

Table 6
Summary of recent studies on climate change impacts on wind resources. For emission scenario details, see the SI.

Study	Emission scenarios	Period of analysis	Results
Karnauskas et al. (2018) [12]	RCP 4.5 (medium) and 8.5 (high)	End of century	Among ten GCMs, inter-model agreement in decreased wind power potential in Great Plains by 8–10% under RCP 4.5–8.5 by 2050 and stronger reductions by 2100 Inter-model agreement in increased wind speeds in Mid-Atlantic under RCP 4.5 by end of century and decreased wind speeds in West across RCPs through end of century Seasonal trends in wind speed changes, e.g., Great Plains reductions primarily occur in winter
Johnson and Erhardt (2016) [75]	SRES A2 (high)	Midcentury	Among four GCM–RCM pairs (two differ from [74]), inter-model agreement in increased average wind energy density by less than 10% in north Texas region Inter-model agreement in decreased wind energy density by up to 20% and 40% in Northeast and Northwest, respectively
Haupt et al. (2016) [76]	SRES A2 (high)	Midcentury	Significant seasonal and spatial variability in climate change impacts on wind speeds using a GCM–RCM pair selected as best reproducing current climate conditions among three GCM–RCM pairs For example, in morning hours, wind speeds in Texas increase by up to 10% in summer and fall but decrease up to 6% in winter and spring, whereas wind speeds in the Northeast increase only in winter
Kulkarni and Huang (2014) [77]	RCP 8.5 (high)	End of century	Among five GCMs, increased average wind speeds in winter of up to 10% in north Texas and Great Plains Regions and decreased average wind speeds in summer of up to 20% in Midwest, Great Plains, and Northeast Among five GCMs, inter-model agreement in increased winter wind speeds in Southeast and north Texas region and decreased summer wind speeds in East, Great Lakes, and Great Plains
Pryor et al. (2012) [73]	SRES A2 (high)	Midcentury	Among eight GCM-RCM pairs, inter-model agreement in increased mean and median wind speed by less than 2% in north Texas through Kansas Inter-model agreement in decreased mean and median wind speed by up to 20% in West, Northwest, Mid-Atlantic, and Northeast
Pryor and Barthelmie (2011) [74]	SRES A2 (high)	Midcentury	Among four GCM–RCM pairs, inter-model agreement in stable or increased mean wind energy density by up to 15% in north Texas region Inter-model agreement in decreased mean wind energy density by up to 15% in Pacific Northwest Among GCM-RCM pairs, mean future wind resource outside 95% confidence interval of historic means in less than 25% of grid cells, indicating modest climate change signal

and availability, which in turn would affect electricity generation from wind turbines [16]. More specifically, climate change could affect inter- and intraday variability of wind resources, which drive the uncertain and variable nature of wind power; or long-term average wind resources, which drive annual generation. Any such long-term average wind resource reductions would continue a trend over recent decades [72]. To forecast wind power under climate change, studies extract wind speed and other variables from GCMs or, to obtain higher spatially and temporally resolved projections, RCMs coupled with GCMs. In either case, most studies extrapolate wind speed from 10 m to 50 m or higher, then convert wind speed and other variables to energy density or power. Alternatively, some studies do not use wind speeds from climate models directly but rather apply changes in wind speeds from current to future climate change conditions to historic observations or reanalysis data sets.

Reviewed studies suggest climate change will decrease average wind resources across a larger area than it will increase them, but large uncertainties remain [12,73–76] (Table 6). In fact, in many regions GCMs disagree on the direction of wind resource changes under climate change. However, based on reviewed studies, GCM-RCM pairs generally indicate that average wind energy density will increase by less than 10% through northern Texas and Kansas and will decrease in the Northeast and Northwest by less than 15% [73–75]. Several papers find significant seasonal and spatial variability in climate change effects on wind resources [12,76,77].

Despite growing publications in this area, large uncertainties remain, and little consensus has emerged on temporal and spatial variability in wind resource changes under climate change. Future research should consider how climate change affects variability of wind power across timescales, from intraday to interannual variability, as in Tobin et al. [78]. Additionally, research should account for wind turbine technology development that could mitigate or exploit wind speed changes instead of assuming static technology, as in most existing studies (although Tobin et al. [78] test the sensitivity of wind power generation to hub height). Finally, research should further investigate heterogeneity in wind resource changes [12,76,79], which will be important to power system operations.

The lack of consensus on future changes in wind power potential under climate change precludes drawing firm links to impacts on power system planning and operations. In general, long-term (i.e., decadal) changes in wind power potential might reduce its capacity value and contribution to decarbonization targets, requiring additional investments in peaking capacity and low-carbon technologies, respectively. Long-term declines in wind generation potential might also result in revenue shortfalls for wind power plants, inhibiting future deployment rates and endangering existing installations. With respect to operations, increased intraday or inter-daily variability would require increased flexibility by the rest of the fleet to meet demand and minimize curtailment, but how variability will change remains unclear. Reduced generation would also result in dispatching alternate technologies, likely increasing costs and emissions.

4.5. Solar generation potential

By altering weather patterns, climate change will affect surface air temperatures and cloud occurrence, type, and dissipation time, which in turn will affect electricity generation by solar photovoltaic (PV) and concentrating solar power (CSP) plants. Because the extinction of solar radiation has an exponential relationship to cloud optical depth, small changes in cloud occurrence, timing, and optical thickness will have large impacts on solar radiation. To forecast solar power potential under climate change, studies typically extract surface air temperature, cloud cover, and clear- and all-sky radiation from GCMs or RCMs coupled with GCMs, although state-of-the-art GCMs and RCMs tend to not represent clouds well [80,81]. General equations then translate these variables into Direct Normal Irradiance and estimate solar PV and CSP generation. As with wind speeds, some studies forecast solar radiation under climate change by adding the change in solar radiation from the present to future climate conditions to reanalysis data sets.

Reviewed studies indicate that solar resources will increase or decrease in some regions in the United States, but in most regions GCM-RCM pairs do not agree on the direction of change in solar resources [60,76,82–85] (Table 7). Specifically, reviewed studies indicate that solar PV generation potential might decrease in California and increase

Table 7
Summary of recent studies on climate change impacts on solar resources. For emission scenario details, see the SI.

Study	Emission scenarios	Period of analysis	Region	Results
Wild et al. (2017) [82]	RCP 8.5 (high)	Midcentury	Nationwide	Across 39 GCMs, inter-model agreement in increased median CSP generation potential by up to 10% in the Southeast No inter-model agreement in CSP generation potential changes elsewhere
Haupt et al. (2016) [76]	SRES A2 (high)	Midcentury	Nationwide	Greater increases in CSP than PV generation potential because of increasing CSP efficiency with air temperature Significant seasonal and spatial variability in climate change impacts on solar radiation using a GCM-RCM pair selected as best reproducing current climate conditions among three GCM-RCM pairs For example, in morning hours, solar radiation in the Southeast increases by up to 5% in summer and winter but decrease by up to 1% in fall and spring
Wild et al. (2015) [13]	RCP 8.5 (high)	Midcentury	Nationwide	Across 39 GCMs, inter-model agreement in increased median solar PV generation potential by up to 3% in the Southeast and decreased median generation potential by up to 3% in California and Pacific Northwest Inter-model agreement in increased air temperatures nationwide; increased all-sky solar radiation and reduced cloud fraction in the Southeast; and decreased clear-sky radiation in the West, Pacific Northwest, and Great Plains, which drive generation potential changes
Duffy (2014) [60]	SRES A2 (high)	Midcentury	California	Across 15 GCMs, increased average PV generation potential by up to 1% in summer and no change in winter
Crook et al. (2011) [85]	SRES A1B (medium)	End of century	Nationwide	Across 2 GCMs, increased average PV generation potential by up to 4% in the Southeast and decreased generation potential elsewhere by up to 10% Across 2 GCMs, decreased average CSP generation potential by up to 10% in the West and Southwest and increased CSP generation potential elsewhere by up 15%

in the Southeast by a few percentage points. Reviewed studies also suggest larger increases in CSP than PV generation across the United States [82,84,85]. Solar resource changes under climate change will likely vary significantly across time and space [76].

Significant work remains to reduce uncertainty for solar generation under climate change. A challenge will be properly accounting for aerosols in climate models, which have driven decadal decreases and increases in solar radiation [86]. In light of Haupt et al. [76], future research should also disaggregate annual results by season and time of day to reveal heterogeneous changes relevant to power system operations. Finally, as RCMs and GCMs improve, studies should quantify how variability in solar output might change from intraday to interannual scales.

Because little consensus exists in the literature, only tentative links can be drawn between changes in solar power and power system planning and operations. Increased solar generation potential might increase the capacity and energy value of solar in the near term, but increases might be limited as peak net demand shifts to early evening hours. Conversely, reduced solar generation potential might increase long-term variability in solar power output and capacity value [87]. Shifts in the short-term variability of solar power might affect flexibility and operational reserve requirements of power systems, while increased solar generation potential might impose increased generation ramping needs on the system. Increases in CSP generation potential will improve its economics, potentially shifting investments from solar PV to CSP. Increasing distributed PV generation potential might also require increased distribution network investments in areas with high distributed PV penetrations. Conversely, reduced PV generation potential in California would need to be offset by increased PV deployment, e.g., by using a greater DC:AC ratio, or be replaced by other low-carbon sources to meet carbon reduction targets.

4.6. Transmission

Climate change might affect resistive losses, maximum capacities, and outage rates of transmission lines, transformers, and substations through increasing air temperature, rainfall, and intensity and frequency of wildfires and storm events [88,89]. Although these impacts have received less attention than climate change impacts on generation and demand, existing studies suggest that climate change will mainly reduce transmission capacity by roughly 2–8% in the United States during peak demand periods by 2100 across emission scenarios. For California, Sathaye et al. [9] estimate that a 5 °C air temperature increase, or the average increase for hot days in August under SRES A2 (high emissions) by 2100, would reduce the maximum capacity of 345-kV, 500-kV, and 765-kV transmission lines by 7–8%. Further, they find that the same increase in air temperature might reduce substation capacities by 1–3% and negligibly affect resistive losses. Bartos et al. [90] estimate that average summertime transmission line capacity reductions across the United States could range from 2% to 6% under RCP 2.6–8.5 (low–high emissions) by midcentury, with the Midwest seeing the largest reductions. Transmission infrastructure failures, including those caused by mechanical and overcurrent issues, could also occur more frequently under climate change [91].

Given the sparsity of the literature on climate impacts on transmission, additional research on all aspects of this issue should be conducted. Research should quantify transmission capacity reductions during peak demand periods, when transmission systems are heavily loaded. Additionally, given the instrumental role high-voltage transmission might play in decarbonization [25,92], future research should explore how transmission expansion might be undercut by climate change.

Reduced transmission line capacities because of climate change might require increased transmission investments to achieve the same transmission capacity. Otherwise, operations during peak demand periods might overload the transmission system or require suboptimal

dispatching. Transmission capacity reductions might also curtail distant wind and solar resources, improving the relative economics of wind and solar investments closer to load. Transmission planning should consider using advanced conductors capable of withstanding high air temperatures [89,93]. With respect to operations, reduced transmission line capacities would affect power flows and potentially exacerbate contingency events. Flexible alternating current transmission system devices could partly compensate for these issues.

5. Climate change effects on power system planning and operations

5.1. Prior literature

Few studies in the United States (or elsewhere) have translated component-level impacts into system planning and operation impacts. Using three long-term planning models, McFarland et al. [18] assess how nationwide increased demand and reduced thermal efficiency because of rising air temperatures under climate change affect investments and generation. Under a high emissions scenario, they project that demand will increase 2–7% through 2050, which would be met by similar generation increases across fuel types. Additionally, capital and operational costs would increase 2–8%, and CO_2 emissions would increase 2–5%. Using a different long-term planning model, Larsen et al. [19] quantify nationwide demand increases and thermal plant efficiency decreases because of warmer air temperatures by midcentury under RCPs 2.6 and 8.5 (low and high emissions). They forecast that generation will need to increase 1–4% across RCPs, mostly from natural gas-fired generators and solar PV. Greater increased growth in peak than average demand requires significant (90–150 GW) investment in peaking combustion turbines. Increased generation and investments increase nationwide electricity expenditures by 4–18%.

5.2. Aggregating component-level impacts to impacts on power system planning and operations

Climate change will likely increase curtailments and reduce efficiencies of thermal generators nationwide; decrease wind resources on average nationwide but have heterogeneous temporal and regional impacts; have heterogeneous regional and temporal impacts on solar resources; increase annual and, to a greater extent, peak electricity demand; and reduce transmission capacity (Section 4; Table 3). In this section, we provide our assessment of how interactions among these impacts might affect power systems during long-term planning, midterm hydrothermal coordination, and short-term (i.e., day-ahead and real-time) operations.

5.2.1. Long-term planning

Interactions among climate change impacts on all power system components surveyed here might impact investment decisions made during long-term planning. Planning primarily aims to ensure resource adequacy or that sufficient capacity exists to meet peak demand plus a planning reserve margin and other system requirements, e.g., flexible capacity. The confluence of increasing annual and peak demand, decreasing transmission capacity, and decreasing firm capacity across generation types will likely require increased investment in transmission and generation assets or in demand response and other demand reduction strategies to maintain the planning reserve margin (Fig. 1). In many U.S. power systems, high demand coincides with peak air temperatures [94], which will likely also exacerbate capacity reductions of thermal and solar PV plants and transmission. Additional investment requirements could be substantial because peak demand alone might increase 10–20% by 2100 (Table 4). Climate change might also lead to a shift from climate-susceptible to climate-resilient technologies, such as from once-through to recirculating cooling [49] or between zero-carbon energy sources depending on regional resource changes. As peak

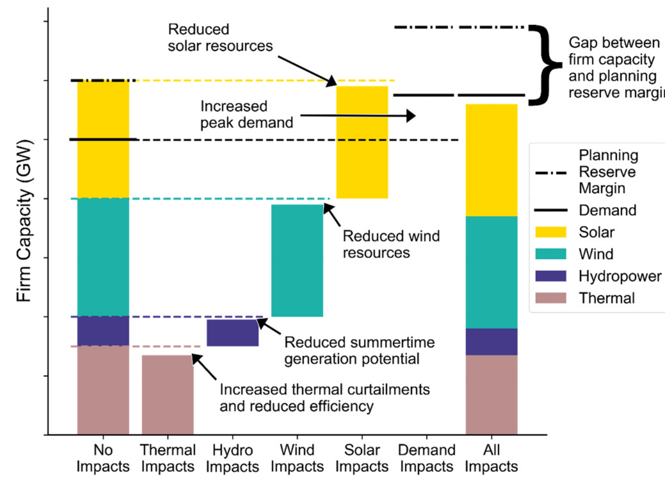

Fig. 1. Potential component-level and system-level impacts of climate change on demand (black line), the planning reserve margin (black dashed line), and firm capacity by generation type (bars). Absolute and relative magnitude of component-level impacts are based on literature surveyed in Section 4. System-level impacts result in firm capacity falling significantly short of the planning reserve margin absent additional investment.

demand grows faster than average demand (Table 4), to meet peak demand systems might also increasingly rely on demand reduction strategies, such as demand response and electricity storage, which could be enabled by electrification efforts [27].

Climate change might also require longer planning horizons. While long-term planning typically spans 10–20 years [95], climate change impacts might take significantly longer to materialize. Thus, the value of investment decisions that can last 50 years or more [22] might differ drastically over a 10- versus 50-year horizon.

An increasingly important aspect of long-term planning is decarbonization, the costs and strategies of which climate change could affect through regional changes in wind and solar resources and increased transmission capacity curtailments. Declining wind and solar resources would yield less greenhouse gas emission reductions per unit of installed capacity, requiring increased investment to achieve the same reductions. Declining wind and solar costs will partly offset additional investment costs [96]. Additionally, region-specific changes in wind and solar resources coupled with increased transmission curtailments could reduce the advantage of remote, high-resource regions relative to local, lower resource regions. Such shifts could undercut decarbonization strategies that rely on large-scale wind deployment in remote resources in tandem with major transmission investments [25,26].

5.2.2. Midterm hydrothermal coordination

In power systems with significant hydropower investments, operators conduct midterm hydrothermal coordination to decompose available hydropower generation from monthly to weekly or daily timescales. As such, climate change will primarily affect midterm coordination through the combination of decreased thermal seasonal capacity, increased seasonal demand, and increased or decreased seasonal hydropower generation (depending on the region). In regions with decreasing (increasing) hydropower resources, hydropower might, depending on competing constraints, be increasingly (decreasingly) concentrated during peak demand hours, requiring more (less) generation from other plants during off-peak hours. Notably, drought conditions might exacerbate all three impacts of climate change, potentially leading to significant changes in scheduling hydropower and underscoring the need for additional studies on the correlation between the impacts.

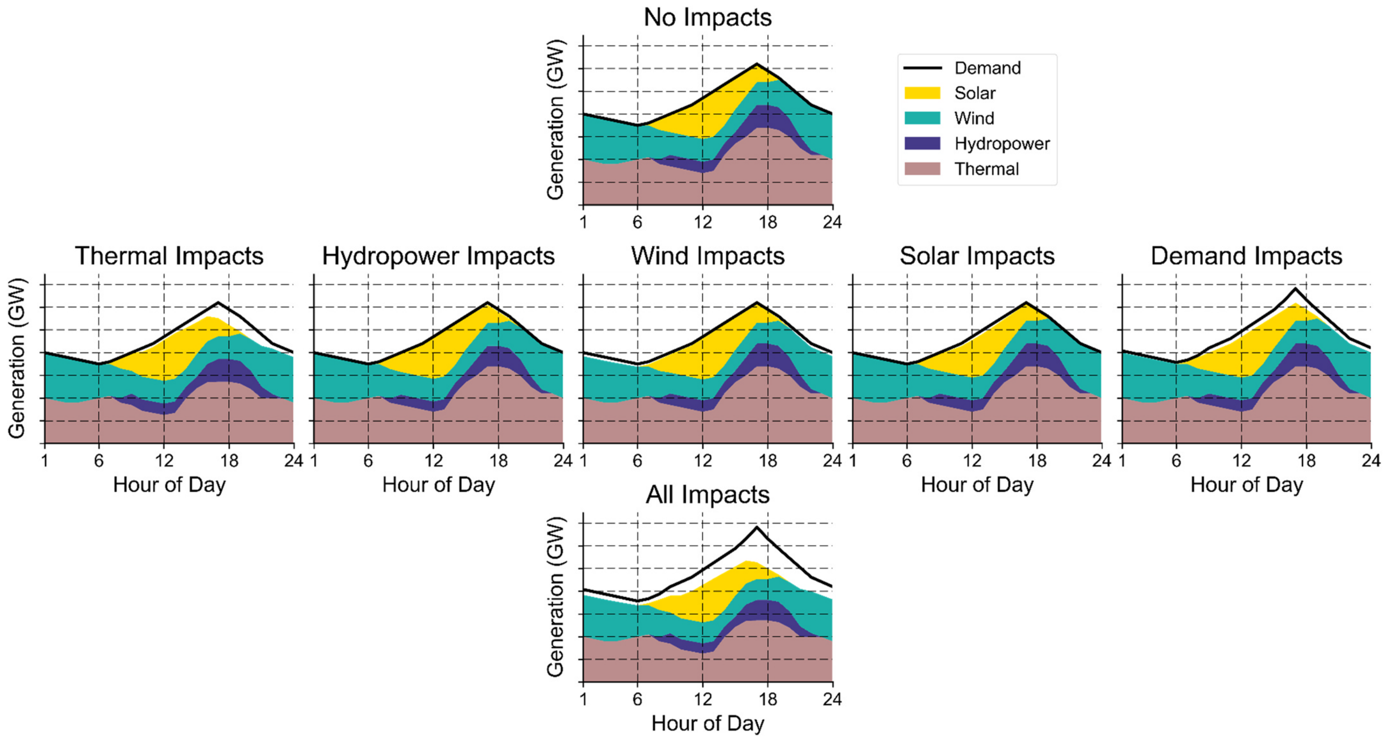

Fig. 2. Illustrative generation profile for a day without climate change impacts (top row) and with potential component-level (middle row) and system-level (bottom row) climate change impacts. Component-level impacts approximate average potential impacts, so impact magnitudes differ among components. The gap between demand and the generation profile indicates a generation shortfall that must be made up via redispatching.

5.2.3. Short-term (day-ahead and real-time) operations

If long-term planning neglects potential climate change impacts, aggregated component-level impacts might result in significant operational challenges. Reduced generation potential, increased curtailments, and increased demand might collectively drive large dispatch changes (Fig. 2), resulting in out-of-merit dispatching or supply shortfalls during peak demand periods. Reduced generation by low-cost resources such as wind, solar, or nuclear might increase generation costs and prices. Thermal curtailments, which provide flexible generation in current systems, plus increased daily peak demand might also strain systems' ramping requirements.

Even if long-term planning accounts for climate change impacts, impacts on demand and wind, solar, and thermal generation on short (hourly to daily) timescales might still interact to affect short-term power system operations. Specifically, climate change might increase uncertainty and variability of generation and demand, requiring increased operational reserve requirements. Increased uncertainty and variability might arise from increased frequency, severity, and correlation of thermal plant curtailments; reduced hydropower availability; more peaked demand; increased transmission capacity curtailments; and potential changes in short-term wind and solar variability, an area of ongoing research. These factors might also drive more peaked electricity prices, potentially increasing arbitrage opportunities for storage and demand response.

5.3. Future research agenda for climate change impacts on power system planning and operations

Many research gaps remain regarding how climate change might affect power system planning and operations. First, future research should aggregate component-level impacts at timescales relevant to power system planning and operations, e.g., monthly and hourly. Such research would reveal interactions and coincidences among component-level impacts, which have significant planning and operational implications. For instance, increasing air temperatures will likely increase demand and might also exacerbate thermal and solar PV plant and transmission capacity reductions. However, generators and transmission are often not colocated with load, so whether these impacts coincide at fine timescales, e.g., hourly, depends on the spatial distribution of temperature changes and other factors. Increasing distributed generation could couple demand increases with generation reductions.

Second, given increasing wind and solar penetrations, studies should further quantify climate change impacts on wind and solar variability. If climate change increases interannual variability of wind and solar generation, systems would need to procure additional capacity to meet peak demand. In decarbonized systems that rely on high penetrations of renewables combined with large-scale electricity storage, increased wind and solar variability might also require more storage. Increasing variability on shorter timescales, e.g., intraday or inter-daily, might also require systems to procure additional reserves and/or flexible resources to maintain system reliability.

Third, existing research on climate change impacts on power systems largely ignores how the power system might evolve during the coming decades. This evolution includes an increasing shift to zero-carbon energy sources and the adoption of new technologies that might mitigate climate change impacts. Both trends could significantly change the impact of climate change on power system planning and operations. For instance, although climate change might significantly curtail thermal generation, the impact of such curtailments diminishes as systems shift from thermal to nonthermal renewable technologies. Conversely, small changes in wind and solar resources become increasingly important in high renewable systems. More climate-resilient technologies might also be increasingly deployed, e.g., by switching to recirculating cooling [49], but little research on such opportunities exists beyond thermal generation. Different wind turbine hub heights, for instance, could exploit differences in wind resource changes across elevations, affecting decarbonization efforts and capacity values.

6. Conclusion

Climate change will likely impact each component of the U.S. bulk electric power system, including by increasing average and peak demand, increasing curtailments of thermal generation and transmission capacity, decreasing summertime hydropower generation in some regions, and decreasing wind and solar resources in some regions. Although some of these component-level impacts might seem small given the current power system's composition, collectively these impacts might significantly affect future power system planning and operations. With respect to planning, increased demand plus reduced firm capacity across generation types might require significant additional investment to maintain planning reserve margins, whereas regional declines in wind and solar resources might require additional zero-carbon investment to meet decarbonization targets. If planning does not account for climate change impacts, then climate change impacts might significantly affect dispatching and lead to out-of-merit dispatches or supply shortfalls. Even if planning accounts for climate change, though, increasing daily peak load, thermal curtailments, and potential changes to wind and solar variability might require changes to system reserve requirements. To better understand these and other potential impacts on planning and operations, future research should model combined component-level impacts at timescales relevant to planning and operations; quantify impacts to wind and solar variability; and account for ongoing shifts in the power system, e.g., from thermal to renewable generation. Future research should also consider how these climate change impacts may alter private investment and financing decisions [97], e.g. by deterring investment in thermal generation due to increased curtailment risk.

While this review focuses on the United States, power systems globally will likely face at least some of the same impacts of climate change on power systems to varying extents. For instance, climate change is expected to increase air temperatures globally [20], which in turn would likely increase peak electricity demand in summertime peaking systems. Additionally, studies find changes in thermal curtailments or to hydropower, wind, or solar resources under climate change in Europe [98–100], China [101], Africa [102], and globally [12,13,62,64,66,84]. Given that all bulk power systems strive to (1) ensure sufficient investment exists to meet peak demand and (2) constantly balance supply with demand, the planning and operational ramifications of climate change impacts discussed above are applicable to bulk power systems globally. Thus, power system planners and operators around the world should consider what changes, if any, need to be made to ensure resilient, reliable, and economic delivery of electricity as climate change intensifies.

Acknowledgments

This work was supported by the Laboratory Directed Research and Development (LDRD) Program at the National Renewable Energy Laboratory. NREL is a national laboratory of the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy operated by the Alliance for Sustainable Energy, LLC. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes. Dr. Haupt was supported by base funds from NCAR, which is supported by the National Science Foundation.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.rser.2018.09.022.

References

[1] U.S. Global Change Research Program. Fourth national climate assessment; 2017.
[2] U.S. Department of Energy. U.S. energy sector vulnerabilities to climate change and extreme weather; 2013.
[3] Rademaekers K, van de Laan J, Boeve S, Lise W, Kirchsteiger C. Investment needs for future adaptation measures in EU nuclear power plants and other electricity generation technologies due to effects of climate change. Eur Comm; 2011. p. 1–222.
[4] Hydro Quebec. Adaptation to climate change. HydroQuebecCom; 2018.
[5] Bonneville Power Administration. BPA prepares for a changing climate. BPAGov 2014.〈https://www.bpa.gov/news/newsroom/Pages/BPA-prepares-for-a-changing-climate.aspx〉. [accessed 3 April 2018].
[6] Lazard. Lazard's levelized cost of energy analysis - version 11.0; 2017.
[7] United Nations Framework Convention on Climate Change. Paris agreement; 2015.
[8] Auffhammer M, Baylis P, Hausman CH. Climate change is projected to have severe impacts on the frequency and intensity of peak electricity demand across the United States. Proc Natl Acad Sci USA 2017;114:1886–91. https://doi.org/10.1073/pnas.1613193114.
[9] Sathaye J a, Dale LL, Larsen PH, Fitts G a, Koy K, Lewis SM, et al. Estimating impacts of warming temperatures on California's electricity system. Glob Environ Chang 2013;23:499–511. https://doi.org/10.1016/j.gloenvcha.2012.12.005.
[10] van Vliet MTH, Yearsley JR, Ludwig F, Vögele S, Lettenmaier DP, Kabat P. Vulnerability of US and European electricity supply to climate change. Nat Clim Chang 2012;2:676–81. https://doi.org/10.1038/nclimate1546.
[11] Miara A, Macknick JE, Vörösmarty CJ, Tidwell VC, Newmark R, Fekete B. Climate and water resource change impacts and adaptation potential for US power supply. Nat Clim Chang 2017;7:793–8. https://doi.org/10.1038/nclimate3417.
[12] Karnauskas KB, Lundquist JK, Zhang L. Southward shift of the global wind energy resource under high carbon dioxide emissions. Nat Geosci 2018;11:38–43.
[13] Wild M, Folini D, Henschel F, Fischer N, Müller B. Projections of long-term changes in solar radiation based on CMIP5 climate models and their influence on energy yields of photovoltaic systems. Sol Energy 2015;116:12–24. https://doi.org/10.1016/j.solener.2015.03.039.
[14] Stanton MCB, Dessai S. A systematic review of the impacts of climate variability and change on electricity systems in Europe. Energy 2016;109:64. https://doi.org/10.1016/j.energy.2016.05.015.
[15] Chandramowli SN, Felder FA. Impact of climate change on electricity systems and markets - A review of models and forecasts. Sustain Energy Technol Assess 2014;5:62–74. https://doi.org/10.1016/j.seta.2013.11.003.
[16] Schaeffer R, Szklo AS, Pereira de Lucena AF, Moreira Cesar Borba BS, Pupo Nogueira LP, Fleming FP, et al. Energy sector vulnerability to climate change: a review. Energy 2012;38:1–12. https://doi.org/10.1016/j.energy.2011.11.056.
[17] Mideksa TK, Kallbekken S. The impact of climate change on the electricity market: a review. Energy Policy 2010;38:3579–85. https://doi.org/10.1016/j.enpol.2010.02.035.
[18] McFarland J, Zhou Y, Clarke L, Sullivan P, Colman J, Jaglom WS, et al. Impacts of rising air temperatures and emissions mitigation on electricity demand and supply in the United States: a multi-model comparison. Clim Change 2015;131:111–25. https://doi.org/10.1007/s10584-015-1380-8.
[19] Larsen K, Larsen J, Delgado M, Herndon W, Mohan S. Assessing the effect of rising temperatures: the cost of climate change to the U.S. Power Sector. Rhodium Group; 2017.
[20] Stocker TF, Dahe Q, Plattner G-K. Technical summary. Intergov Panel Clim Chang Phys Sci Basis; 2013.
[21] Auffhammer M, Hsiang SM, Schlenker W, Sobel A. Global climate models and climate data: A user guide for economists; 2011.
[22] Rode DC, Fischbeck PS, Páez AR. The retirement cliff: power plant lives and their policy implications. Energy Policy 2017;106:222–32. https://doi.org/10.1016/j.enpol.2017.03.058.
[23] Deep Decarbonization Pathways Project. Pathways to deep decarbonization; 2015.
[24] The White House. United States mid-century strategy for deep decarbonization; 2016.
[25] U.S. National Renewable Energy Laboratory. Eastern wind integration and transmission study; 2011.
[26] Lasher W. The competitive renewable energy zones process. ERCOT 2014. 〈https://www.energy.gov/sites/prod/files/2014/08/f18/c_lasher_qer_santafe_presentation.pdf〉. [Accessed 16 April 2018].
[27] Steinberg D, Bielen D, Eichman J, Eurek K, Logan J, Mai T, et al. Electrification & decarbonization: Exploring U.S. energy use and greenhouse gas emissions scenarios with widespread electrification and power sector decarbonization. Natl Renew Energy Lab 2017.
[28] Lew D, Brinkman G, Ibanez E, Florita A, Heaney M, Hodge B, et al. The Western wind and solar integration study phase 2. Natl Renew Energy Lab 2013.
[29] McCall J, Macknick J, Macknick J. Water-related power plant curtailments: an overview of incidents and contributing factors. Natl Renew Energy Lab 2016. https://doi.org/10.2172/1338176.
[30] North American Electric Reliability Corporation. Polar vortex review; 2014.
[31] Taylor KE, Stouffer RJ, Meehl G a. An overview of CMIP5 and the experiment design. Bull Am Meteorol Soc 2012;93:485–98. https://doi.org/10.1175/BAMS-D-11-00094.1.
[32] Flato G, Marotzke J. Chapter 9: evaluation of climate models. Intergov Panel Clim Chang Phys Sci Basis; 2013.
[33] Alley RB, et al. Summary for policymakers. Intergov Panel Clim Chang Phys Sci Basis; 2007.

[34] Li DHW, Yang L, Lam JC. Impact of climate change on energy use in the built environment in different climate zones - a review. Energy 2012;42:103–12. https://doi.org/10.1016/j.energy.2012.03.044.
[35] Allen MR, Fernandez SJ, Fu JS, Olama MM. Impacts of climate change on sub-regional electricity demand and distribution in the southern United States. Nat Energy 2016:1. https://doi.org/10.1038/nenergy.2016.103.
[36] Sullivan P, Colman J, Kalendra E. Predicting the response of electricity load to climate change; 2015.
[37] Coffey B, Stern A, Sue Wing I. Climate change impacts on U.S. electricity demand: Insights from micro-consistent aggregation of a structural model. 2015 Int. Energy Work; 2015.
[38] Jentsch MF, James PAB, Bourikas L, Bahaj ABS. Transforming existing weather data for worldwide locations to enable energy and building performance simulation under future climates. Renew Energy 2013;55:514–24. https://doi.org/10.1016/j.renene.2012.12.049.
[39] Wan KKW, Li DHW, Pan W, Lam JC. Impact of climate change on building energy use in different climate zones and mitigation and adaptation implications. Appl Energy 2012;97:274–82. https://doi.org/10.1016/j.apenergy.2011.11.048.
[40] Dirks JA, Gorrissen WJ, Hathaway JH, Skorski DC, Scott MJ, Pulsipher TC, et al. Impacts of climate change on energy consumption and peak demand in buildings: a detailed regional approach. Energy 2015;79:20–32. https://doi.org/10.1016/j.energy.2014.08.081.
[41] Huang J, Gurney KR. Impact of climate change on U.S. building energy demand: sensitivity to spatiotemporal scales, balance point temperature, and population distribution. Clim Change 2016;137:171–85. https://doi.org/10.1007/s10584-016-1681-6.
[42] Fonseca FR, Jaramillo P, Berges M, Severnini E. Impacts of climate change on demand in the Tennessee Valley Authority region. Prep 2018.
[43] Kraucunas I, Clarke L, Dirks J, Hathaway J, Hejazi M, Hibbard K, et al. Investigating the nexus of climate, energy, water, and land at decision-relevant scales: the platform for regional integrated modeling and analysis (PRIMA). Clim Change 2015;129:573–88. https://doi.org/10.1007/s10584-014-1064-9.
[44] Zhou Y, Eom J, Clarke L. The effect of global climate change, population distribution, and climate mitigation on building energy use in the U.S. and China. Clim Change 2013;119:979–92. https://doi.org/10.1007/s10584-013-0772-x.
[45] Burillo D, Chester MV, Ruddell B, Johnson N. Electricity demand planning forecasts should consider climate non-stationarity to maintain reserve margins during heat waves. Appl Energy 2017;206:267–77. https://doi.org/10.1016/j.apenergy.2017.08.141.
[46] Jaglom WS, McFarland JR, Colley MF, Mack CB, Venkatesh B, Miller RL, et al. Assessment of projected temperature impacts from climate change on the U.S. electric power sector using the Integrated Planning Model. Energy Policy 2014;73:524–39. https://doi.org/10.1016/j.enpol.2014.04.032.
[47] Rutberg MJ, Delgado A, Herzog HJ, Ghoniem AF. A system-level generic model of water use at power plants and its application to regional water use estimation. In: Proceedings of the ASME 2011 International Mechanical Engineering Congress and Exposition; 2011, p. 1–11.
[48] Koch H, Vögele S. Dynamic modelling of water demand, water availability and adaptation strategies for power plants to global change. Ecol Econ 2009;68:2031–9. https://doi.org/10.1016/j.ecolecon.2009.02.015.
[49] van Vliet MTH, Wiberg D, Leduc S, Riahi K. Power-generation system vulnerability and adaptation to changes in climate and water resources. Nat Clim Chang 2016;6:375–80. https://doi.org/10.1038/nclimate2903.
[50] Bartos MD, Chester MV. Impacts of climate change on electric power supply in the Western United States. Nat Clim Chang 2015;5:748–52. https://doi.org/10.1038/NCLIMATE2648.
[51] U.S. Global Change Research Program. Climate change impacts in the United States; 2014.
[52] Henry CL, Pratson LF. Effects of environmental temperature change on the efficiency of coal- and natural gas-fired power plants. Environ Sci Technol 2016;50:9764–72. https://doi.org/10.1021/acs.est.6b01503.
[53] Liu L, Hejazi M, Li H, Forman B, Zhang X. Vulnerability of US thermoelectric power generation to climate change when incorporating state-level environmental regulations. Nat Energy 2017;2:17109. https://doi.org/10.1038/nenergy.2017.109.
[54] Ganguli P, Kumar D, Ganguly AR. US power production at risk from water stress in a changing climate. Sci Rep 2017;7:1–13. https://doi.org/10.1038/s41598-017-12133-9.
[55] Guerra OJ, Reklaitis GV. Advances and challenges in water management within energy systems. Renew Sustain Energy Rev 2018;82:4009–19. https://doi.org/10.1016/j.rser.2017.10.071.
[56] Talati S, Zhai H, Morgan MG. Water impacts of CO_2 emission performance standards for fossil fuel-fired power plants. Environ Sci Technol 2014;48:11769–76. https://doi.org/10.1021/es502896z.
[57] Schaefli B. Projecting hydropower production under future climates: a guide for decision-makers and modelers to interpret and design climate change impact assessments. Wiley Interdiscip Rev Water 2015;2:271–89. https://doi.org/10.1002/wat2.1083.
[58] Macknick J, Zhou E, Connell MO, Brinkman G, Miara A, Ibanez E, et al. Water and climate impacts on power system operations: the importance of cooling systems and demand response measures. Natl Renew Energy Lab 2016:64.
[59] Macknick J, Cohen S, Newmark R, Martinez A, Sullivan P, Tidwell V. Water constraints in an electric sector capacity expansion model. Natl Renew Energy Lab 2015.
[60] Duffy PB. Final project report climate change impacts on generation of wind, solar, and hydropower in California; 2014.
[61] Tarroja B, AghaKouchak A, Samuelsen S. Quantifying climate change impacts on hydropower generation and implications on electric grid greenhouse gas emissions and operation. Energy 2016;111:295–305. https://doi.org/10.1016/j.energy.2016.05.131.
[62] Schewe J, Heinke J, Gerten D, Haddeland I, Arnell NW, Clark DB, et al. Multimodel assessment of water scarcity under climate change. Proc Natl Acad Sci USA 2014;111:3245–50. https://doi.org/10.1073/pnas.1222460110.
[63] Madani K, Lund JR. Estimated impacts of climate warming on California's high-elevation hydropower. Clim Change 2010;102:521–38. https://doi.org/10.1007/s10584-009-9750-8.
[64] Turner SWD, Ng JY, Galelli S. Examining global electricity supply vulnerability to climate change using a high-fidelity hydropower dam model. Sci Total Environ 2017;590–591:663–75. https://doi.org/10.1016/j.scitotenv.2017.03.022.
[65] Hagemann S, Chen C, Clark DB, Folwell S, Gosling SN, Haddeland I, et al. Climate change impact on available water resources obtained using multiple global climate and hydrology models. Earth Syst Dyn 2013;4:129–44. https://doi.org/10.5194/esd-4-129-2013.
[66] van Vliet MTH, van Beek LPH, Eisner S, Flörke M, Wada Y, Bierkens MFP. Multi-model assessment of global hydropower and cooling water discharge potential under climate change. Glob Environ Chang 2016;40:156–70. https://doi.org/10.1016/j.gloenvcha.2016.07.007.
[67] Boehlert B, Strzepek KM, Gebretsadik Y, Swanson R, McCluskey A, Neumann JE, et al. Climate change impacts and greenhouse gas mitigation effects on U.S. hydropower generation. Appl Energy 2016;183:1511–9. https://doi.org/10.1016/j.apenergy.2016.09.054.
[68] Naz BS, Kao S-C, Ashfaq M, Gao H, Rastogi D, Gangrade S. Effects of climate change on streamflow extremes and implications for reservoir inflow in the United States. J Hydrol 2018;556:359–70. https://doi.org/10.1016/j.jhydrol.2017.11.027.
[69] Hamlet AF, Lee S-Y, Mickelson KEB, Elsner MM. Effects of projected climate change on energy supply and demand in the Pacific Northwest and Washington State. Clim Change 2010;102:103–28. https://doi.org/10.1007/s10584-010-9857-y.
[70] Kao SC, Sale MJ, Ashfaq M, Uria Martinez R, Kaiser DP, Wei Y, et al. Projecting changes in annual hydropower generation using regional runoff data: an assessment of the United States federal hydropower plants. Energy 2015;80:239–50. https://doi.org/10.1016/j.energy.2014.11.066.
[71] Parkinson SC, Djilali N. Robust response to hydro-climatic change in electricity generation planning. Clim Change 2015;130:475–89. https://doi.org/10.1007/s10584-015-1359-5.
[72] Vautard R, Cattiaux J, Yiou P, Thépaut JN, Ciais P. Northern Hemisphere atmospheric stilling partly attributed to an increase in surface roughness. Nat Geosci 2010;3:756–61. https://doi.org/10.1038/ngeo979.
[73] Pryor SC, Barthelmie RJ, Schoof JT. Past and future wind climates over the contiguous USA based on the North American regional climate change assessment program model suite. J Geophys Res Atmos 2012:117. https://doi.org/10.1029/2012JD017449.
[74] Pryor SC, Barthelmie RJ. Assessing climate change impacts on the near-term stability of the wind energy resource over the United States. Proc Natl Acad Sci USA 2011;108:8167–71. https://doi.org/10.1073/pnas.1019388108.
[75] Johnson DL, Erhardt RJ. Projected impacts of climate change on wind energy density in the United States. Renew Energy 2016;85:66–73. https://doi.org/10.1016/j.renene.2015.06.005.
[76] Haupt SE, Copeland J, Cheng WYY, Zhang Y, Ammann C, Sullivan P. A method to assess the wind and solar resource and to quantify interannual variability over the United States under current and projected future climate. J Appl Meteorol Climatol 2016;55:345–63. https://doi.org/10.1175/JAMC-D-15-0011.1.
[77] Kulkarni S, Huang H-P. Changes in surface wind speed over North America from CMIP5 model projections and implications for wind energy. Adv Meteorol 2014;2014:10. https://doi.org/10.1155/2014/292768.
[78] Tobin I, Jerez S, Vautard R, Thais F, Van Meijgaard E, Prein A, et al. Climate change impacts on the power generation potential of a European mid-century wind farms scenario. Environ Res Lett 2016:11. https://doi.org/10.1088/1748-9326/11/3/034013.
[79] Goddard SD, Genton MG, Hering AS, Sain SR. Evaluating the impacts of climate change on diurnal wind power cycles using multiple regional climate models. Environmetrics 2015;26:192–201. https://doi.org/10.1002/env.2329.
[80] Boucher O, Randall D. Chapter 7: clouds and aerosols. Intergov Panel Clim Chang Phys Sci Basis; 2013.
[81] Lauer A, Hamilton K. Simulating clouds with global climate models: a comparison of CMIP5 Results with CMIP3 and satellite data. J Clim 2013;26:3823–45. https://doi.org/10.1175/JCLI-D-12-00451.1.
[82] Wild M, Folini D, Henschel F. Impact of climate change on future concentrated solar power (CSP) production. AIP Conf Proc 2017. https://doi.org/10.1063/1.4975562.
[83] Folini D, Dallafior TN, Hakuba MZ, Wild M. Trends of surface solar radiation in unforced CMIP5 simulations. J Geophys Res 2017;122:469–84. https://doi.org/10.1002/2016JD025869.
[84] Huber I, Bugliaro L, Ponater M, Garny H, Emde C, Mayer B. Do climate models project changes in solar resources? Sol Energy 2016;129:65–84. https://doi.org/10.1016/j.solener.2015.12.016.
[85] Crook JA, Jones LA, Forster PM, Crook R. Climate change impacts on future photovoltaic and concentrated solar power energy output. Energy Environ Sci 2011;4:3101. https://doi.org/10.1039/c1ee01495a.
[86] Wild M. Decadal changes in radiative fluxes at land and ocean surfaces and their relevance for global warming. Wiley Interdiscip Rev Clim Chang 2016;7:91–107.

https://doi.org/10.1002/wcc.372.
[87] Bryce R, Losada I, Hodge B, Martinez-anido CB. Consequences of neglecting the interannual variability of the solar resource: a case study of photovoltaic power among the Hawaiian Islands. [In press]. Sol Energy2018:61–75. https://doi.org/10.1016/j.solener.2018.03.085.
[88] Ward DM. The effect of weather on grid systems and the reliability of electricity supply. Clim Change 2013;121:103–13. https://doi.org/10.1007/s10584-013-0916-z.
[89] U.S. Department of Energy. Climate change and the U.S. energy sector: regional vulnerabilities and resilience solutions; 2015.
[90] Bartos M, Chester M, Johnson N, Gorman B, Eisenberg D, Linkov I, et al. Impacts of climate change on electric transmission capacity and peak electricity load in the United States. Environ Res Lett 2016;11:1–13. https://doi.org/10.1088/1748-9326/11/11/114008.
[91] Burillo D, Chester M, Ruddell B. Electric grid vulnerabilities to rising air temperatures in Arizona. Procedia Eng 2016;145:1346–53. https://doi.org/10.1016/j.proeng.2016.04.173.
[92] International Energy Agency. Status of power system transformation 2017: system integration and local grids. IEA 2017. https://doi.org/10.1787/9789264278820-en.
[93] Gellings CW, Yeager KE. Transforming the electric infrastructure. Phys Today 2004;57:45–51. https://doi.org/10.1063/1.1878334.
[94] Bramer LM, Rounds J, Burleyson CD, Fortin D, Hathaway J, Rice J, et al. Evaluating penalized logistic regression models to predict heat-related electric grid stress days. Appl Energy 2017;205:1408–18. https://doi.org/10.1016/j.apenergy.2017.09.087.
[95] Wilson R, Biewald B. Best practices in electric utility integrated resource planning; 2013.
[96] U.S. National Renewable Energy Laboratory. Annual technology baseline 2016; 2016.
[97] Campiglio E, Dafermos Y, Monnin P, Ryan-Collins J, Schotten G, Tanaka M. Climate change challenges for central banks and financial regulators. Nat Clim Chang 2018;8:462–8. https://doi.org/10.1038/s41558-018-0175-0.
[98] van Vliet MTH, Vögele S, Rübbelke D. Water constraints on European power supply under climate change: impacts on electricity prices. Environ Res Lett 2013;8:035010. https://doi.org/10.1088/1748-9326/8/3/035010.
[99] Davy R, Gnatiuk N, Pettersson L, Bobylev L. Climate change impacts on wind energy potential in the European domain with a focus on the Black Sea. Renew Sustain Energy Rev 2018;81:1652–9. https://doi.org/10.1016/j.rser.2017.05.253.
[100] Jerez S, Tobin I, Vautard R, Montavez JP, Lopez-Romero JM, Thais F, et al. The impact of climate change on photovoltaic power generation in Europe. Nat Commun 2015;6:10014. https://doi.org/10.1038/ncomms10014.
[101] Liu X, Tang Q, Voisin N, Cui H. Projected impacts of climate change on hydropower potential in China. Hydrol Earth Syst Sci 2016;20:3343–59. https://doi.org/10.5194/hess-20-3343-2016.
[102] Fant C, Adam Schlosser C, Strzepek K. The impact of climate change on wind and solar resources in southern Africa. Appl Energy 2015;161:556–64. https://doi.org/10.1016/j.apenergy.2015.03.042.